

Analysis of the Z Distribution of Young Objects in the Galactic Thin Disk

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Abstract—We have obtained new estimates of the Sun’s distance from the symmetry plane Z_{\odot} and the vertical disk scale height h using currently available data on stellar OB associations, Wolf-Rayet stars, HII regions, and Cepheids. Based on individual determinations, we have calculated the mean $Z_{\odot} = -16 \pm 2$ pc. Based on the model of a self-gravitating isothermal disk for the density distribution, we have found the following vertical disk scale heights: $h = 40.2 \pm 2.1$ pc from OB associations, $h = 47.8 \pm 3.9$ pc from Wolf-Rayet stars, $h = 48.4 \pm 2.5$ pc from HII regions, and $h = 66.2 \pm 1.6$ pc from Cepheids. We have estimated the surface, $\Sigma = 6 \text{ kpc}^{-2}$, and volume, $D(Z_{\odot}) = 50.6 \text{ kpc}^{-3}$, densities from a sample of OB associations. We have found that there could be ≈ 5000 OB associations in the Galaxy.

INTRODUCTION

The Sun is known to be located not exactly in the Galactic plane but to the north of it at a distance of about 20 pc. Two terms are used: (a) the Sun’s height above the Galactic plane and (b) the Sun’s position relative to the symmetry plane. The height is positive and is usually designated as h_{\odot} . The Sun’s position relative to the symmetry plane differs from the height only by its sign and is usually designated as Z_{\odot} . In this paper, we prefer to use Z_{\odot} . There are a number of stellar-astronomy problems whose solution requires knowing an accurate value of this quantity. For example, these include the problems of constructing the Galactic orbit of the Sun or establishing a highly accurate system of Galactic coordinates.

As a rule, the vertical disk scale height h is determined simultaneously with the constant Z_{\odot} . When analyzing the distribution of young objects, we are dealing with the properties of the Galactic thin disk. Different authors use different models of the density distribution in the disk. This is either the model of an exponential density distribution (see, e.g., Joshi 2007), or the model of a self-gravitating isothermal disk (see, e.g., Conti and Vacca 1990), or the Gaussian model (see, e.g., Maiz-Apellániz 2001). Other models are also applied (Rosslowe and Crowther 2015). Ultimately, such determinations are important for constructing a present-day model of the Galactic disk.

Different authors have repeatedly determined Z_{\odot} using young O- and B-type stars, open clusters, Cepheids, infrared sources, molecular clouds, and other objects. The methods of estimating Z_{\odot} are also very diverse. One of the first reviews of such determinations was published by van Tulder (1942); he found $Z_{\odot} = -13.5 \pm 1.9$ pc as a mean value from several samples of various stars.

Таблица 1: Determinations of Z_{\odot} by different authors from different data

Reference	Z_{\odot} , pc	Sample
Toller (1990)	-12.8 ± 2.9	properties of dust from Pioneer 10 data
Conti and Vacca (1990)	-15 ± 3	101 Wolf-Rayet stars, $r < 4.5$ kpc
Brand and Blitz (1993)	-13 ± 7	64 molecular clouds, $r : 0.7\text{--}2$ kpc
Humphreys and Larsen (1995)	-20.5 ± 3.5	optical star counts
Hammersley et al. (1995)	-15.5 ± 3	IR COBE, IRAS, and TMGS data
Binney et al. (1997)	-14 ± 4	IR COBE/DIRBE data
Méndez, van Altena (1998)	-27 ± 3	star counts at low latitudes
Maiz-Apellániz (2001)	-24.2 ± 1.7	3382 Hipparcos OB stars, $r < 350$ pc
Reed (2006)	-19.6 ± 2.1	2488 OB stars, $r < 1.2$ kpc
Piskunov et al. (2006)	-22 ± 4	254 open clusters, $r < 850$ pc
Yoshi (2007)	-17 ± 3	537 open clusters, $r < 4$ kpc
Bobylev (2013)	-23 ± 5	365 classical Cepheids, $r < 4$ kpc
Mean	-18.6 ± 1.4	

A review of present-day determinations can be found, for example, in Humphreys and Larsen (1995) or Reed (2006). Selected results are given in Table 1, which we will comment on in more detail.

Toller (1990) studied the distribution of interstellar Galactic dust on the celestial sphere based on Pioneer 10 spacecraft observations. He calculated the value of Z_{\odot} in Table 1 as the mean of three results obtained independently.

Conti and Vacca (1990) estimated the photometric distances of 157 Wolf-Rayet stars. These were all the known stars of this class at that time. To determine Z_{\odot} , they used 101 stars from the solar neighborhood with a radius $r < 4.5$ kpc.

Brand and Blitz (1993) found Z_{\odot} using data on the distribution of 64 molecular clouds in the range of heliocentric distances 0.7–2 kpc. They did not consider the nearest clouds, closer than 0.7 kpc, to eliminate the influence of the Gould Belt. The distances to the clouds were estimated photometrically.

Hammersley et al. (1995) used infrared data from the COBE (COsmic Background Explorer) and IRAS (InfraRed Astronomical Satellite, 1988) satellites and the TMGS (Two-Micron Galactic Survey; Garzón et al. 1993) catalog for their star counts.

Humphreys and Larsen (1995) made the star counts in 12 Palomar Sky Survey fields near the North and South Galactic poles. Stars of the thin Galactic disk were assumed to form the basis of the sample. The ratio of the numbers of stars in different hemispheres was derived directly from the counts. The Z_{\odot} estimate followed from a comparison with the model distribution of stars in the Galactic disk. The model of the Galaxy by Bahcall and Soneira (1980) was used for this purpose.

In contrast, Méndez and van Altena (1998) made the star counts at low Galactic latitudes. The Guide Star Catalog (Lasker et al. 1990) served as the basis. In this zone, the results of comparing the star counts with the model distribution of stars depend strongly on the proper allowance for interstellar extinction. Therefore, Méndez and van Altena (1988) first developed their model of the 3D distribution of absorbing matter.

Binney et al. (1997) used infrared photometric data from the DIRBE space experiment performed on the COBE satellite. They mapped the surface brightness distribution in the inner Galaxy ($|l| \leq 30^\circ$, $|b| \leq 15^\circ$) by taking into account the model of a central bar. By analyzing the observed distribution, they could reach a conclusion about Z_\odot .

Maiz-Apellániz (2001) used 3382 stars of spectral types from O to B5 with their trigonometric parallaxes from the Hipparcos (1997) catalogue. These stars are located in the solar neighborhood with a radius $r < 350$ pc and were selected under the condition $|b| > 5^\circ$; therefore, the stars lying directly in the Galactic plane, where the interstellar extinction is great, were discarded. The parallaxes were corrected for the Lutz-Kelker bias. The observed distribution of stars was fitted by the model of a self-gravitating isothermal disk with two parameters: Z_\odot and the vertical disk scale height h .

Reed (2006) estimated Z_\odot using 2488 OB stars from the solar neighborhood with a radius $r < 1.2$ kpc. The distances to these stars were determined photometrically (with a relative error of about 20%).

Piskunov et al. (2006) estimated Z_\odot based on a sample of open stars clusters from the ASCC-2.5 catalog in the solar neighborhood with a radius of 850 pc. They showed the catalog of program clusters to be complete at this distance.

Joshi (2007) analyzed the spatial distribution of 537 fairly young (younger than 300 Myr) open star clusters from the solar neighborhood with a radius $r < 4$ kpc. The distance and age estimates were taken from various catalogs. The clusters associated with the Gould Belt were excluded from consideration.

Bobylev (2013) considered the spatial distribution of classical Cepheids in the solar neighborhood with a radius $r < 4$ kpc. The distances to the Cepheids were estimated based on the well-known period–luminosity relation. The relative error in the stellar distances determined by this method is 10%–15%. No constraints were imposed on the pulsation period; the mean age of the Cepheids in this sample can be roughly estimated to be 100 Myr.

It can be seen from Table 1 that the model–dependent estimates (star counts, columns 4–7 in the Table) and the results of direct calculations agree satisfactorily between themselves. There is no noticeable correlation between Z_\odot and the age of objects. The last column of Table 1 gives the mean Z_\odot with the error of the mean calculated from 12 results.

The goal of this paper is to redetermine Z_\odot and h from the currently available data on young objects. These are stellar OB associations, HII regions, Wolf-Rayet stars, and Cepheids. Galactic masers with measured trigonometric parallaxes located in the regions of active star formation also belong to them.

METHODS

In the case of an exponential density distribution, the observed histogram of the distribution of objects along the Z coordinate axis is described by the expression

$$N(Z) = N_1 \exp\left(-\frac{|Z - Z_\odot|}{h_1}\right), \quad (1)$$

where N_1 is the normalization coefficient.

If the model of a self-gravitating isothermal disk is used for the density distribution, then the observed frequency distribution of objects along the Z axis is described by the formula (Spitzer 1942; Conti and Vacca 1990)

$$N(Z) = N_2 \operatorname{sech}^2\left(\frac{Z - Z_\odot}{\sqrt{2} h_2}\right). \quad (2)$$

When the results are compared, it should be kept in mind that in model (2) different authors use either two, $N(Z) = N_2 \operatorname{sech}^2[(Z - Z_\odot)/2h]$ (Maiz-Apellániz, 2001; Buckner and Froebrich, 2014), or one, $N(Z) = N_2 \operatorname{sech}^2[(Z - Z_\odot)/h]$ (Marshall et al., 2006), as the coefficient in the denominator.

Finally, the observed frequency distribution of objects along the Z axis for the Gaussian model is described by the formula

$$N(Z) = N_3 \exp\left[-\frac{1}{2}\left(\frac{Z - Z_\odot}{h_3}\right)^2\right]. \quad (3)$$

Interestingly, when analyzing the Z distribution of OB5 stars based on Eqs. (2) and (3), Maiz-Apellániz (2001) found the vertical scale height h_i to be determined with smaller errors based on Eq. (2). In contrast, when studying OB stars based on Eqs. (1) and (3), Elias et al. (2006) showed the vertical scale height h to be determined more accurately based on Eq. (3). Therefore, the model of a self-gravitating isothermal disk (2) is the most attractive one among the three described models.

The vertical disk scale heights h_i determined by different authors from different data based on models (1), (2), and (3) are given in Table 2. Stothers and Frogel (1974) studied ≈ 1000 O–B5 stars closely associated with the Gould Belt. Reed (2000) considered up to 4000 OB stars with photometric distances in the solar neighborhood with a radius of 4 kpc. The analysis in Elias et al. (2006) was based on a sample of 553 Hipparcos O–B6 stars, with the Gould Belt stars having been excluded. The sample in Joshi (2007) consisted of 2030 OB stars and contained no Gould Belt stars.

The collected results lead us to conclude that the vertical disk scale heights determined using different models (a) agree satisfactorily between themselves if they are applied to samples of the same age and (b) differ noticeably in the case of samples of different ages.

DATA

(1) We use the data on known OB associations with reliable distance estimates from Melník and Dambis (2009). The distances derived by these authors were reconciled with the Cepheid scale. The catalog contains 91 OB associations; the distances to them do not exceed $r = 3.5$ kpc. The designations of associations including stars of spectral types up to B9 (for example, Cyg OB9) are encountered in the catalog. On this basis, we can conclude that the upper age limit is ≈ 60 –80 Myr. Melník and Dambis (2009) estimated the errors in the distances to these OB associations to be 10–15%.

(2) The Wolf-Rayet stars described by Rosslowe and Crowther (2015) constitute another sample. This is the most complete sample of Galactic stars of this type to date. Note that Rosslowe and Crowther studied their Z distribution. A model based on the

Таблица 2: Determinations of the vertical disk scale height $h_i, i = 1, 2, 3$ from data based on three models: (1), (2), and (3)

Reference	h_1 , pc	h_2 , pc	h_3 , pc	Sample
Stothers and Frogel (1974)	46 ± 7	—	48 ± 2	B0-B5, 0–200 pc
Stothers and Frogel (1974)	70 ± 3	—	61 ± 3	B0-B5, 0–800 pc
Conti and Vacca (1990)	—	45 ± 5	—	WR stars
Reed (2000)	45	—	—	OB stars
Maiz-Apellániz (2001)	—	34.2 ± 2.5	62.8 ± 4.7	OB stars (*)
Bonatto et al. (2006)	48 ± 3	—	—	SCs, <200 Myr
Bonatto et al. (2006)	150 ± 27	—	—	SCs, 0.2–1 Gyr
Elias et al. (2006)	34 ± 2	—	30 ± 2	OB stars
Piskunov et al. (2006)	56 ± 3	—	74 ± 3	254 OSCs
Yoshi (2007)	$56.9^{+3.8}_{-3.4}$	—	—	537 OSCs
Yoshi (2007)	$61.4^{+2.7}_{-2.4}$	—	—	OB stars

WR: Wolf-Rayet stars; OSCs: open star clusters; (*): the value of h_2 from Maiz-Apellániz (2001) should be multiplied by $\sqrt{2}$ for its comparison with the result from Conti and Vacca (1990).

Cauchy distribution was used to determine the disk scale height. Rosslowe and Crowther (2015) themselves estimated new distances for 246 stars. They added 108 more stars with known distances from the van der Hucht (2001) catalog to them and produced a sample of 354 stars. All these stars are located within 35 kpc of the Sun. A new analysis of these data using various constraints is of interest. First of all, very distant stars need to be excluded, because the effect due to a large-scale warp of the Galactic thin disk, in particular, a warp of the neutral hydrogen layer, must have a noticeable influence at great distances from the Sun (more than 8–10 kpc). Note that Rosslowe and Crowther (2015) give individual estimates of the random errors in the distances for 246 stars from their list. For the 108 stars from the van der Hucht (2001) catalog that have no such estimates, we assume the distance error to be 20%.

(3) We use the sample of classical Cepheids belonging to our Galaxy described by Mel’nik et al. (2015). This is the most complete sample of such objects with known proper motions and radial velocities to date. This sample contains 674 stars whose distances were determined from the most recent calibrations using both optical and infrared photometric observational data. We assume the error in the distance to a star determined by the Monte Carlo method to be 10%.

(4) We use a sample of Galactic masers with measured trigonometric parallaxes. These sources, associated with very young stars, are located in regions of active star formation. Highly accurate astrometric VLBI measurements of the trigonometric parallaxes and proper motions have already been performed for more than 120 such masers by several teams in the USA, Japan, Europe, and Australia (Reid et al. 2014). The error in the stellar parallax determined by this method is, on average, less than 10%.

We compiled our sample based on a number of publications. The paper of Xu et al. (2013) is devoted to masers in the Local Arm. The review of Reid et al. (2014) contains data of 103 masers. Subsequently, the publications of these authors with improvements and

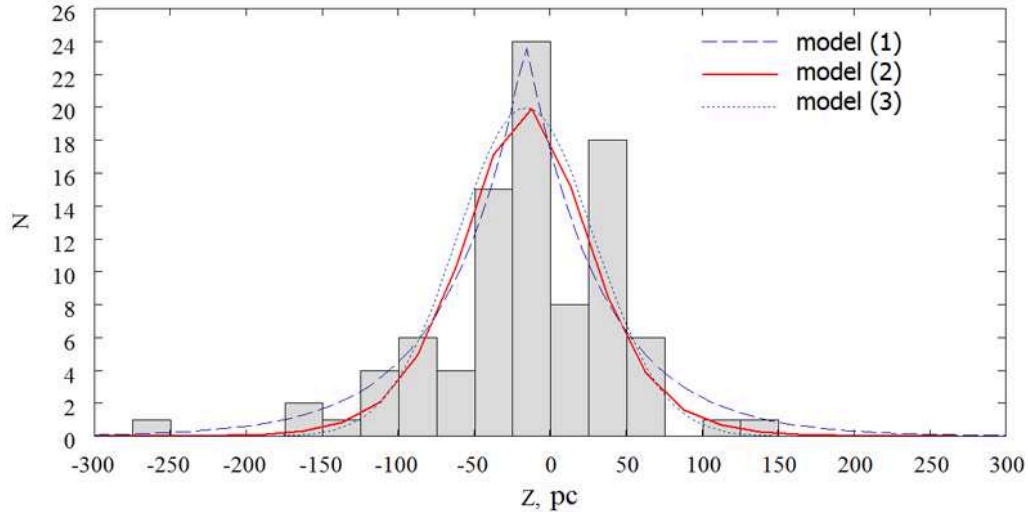


Рис. 1: Histogram of the Z distribution of OB associations.

additions devoted to the analysis of masers in individual Galactic spiral arms appeared. The papers by Sanna et al. (2014), Sato et al. (2014), Wu et al. (2014), Choi et al. (2014), and Hachisuka et al. (2015) are devoted to the inner Galaxy, the Scutum Arm, the Carina–Sagittarius Arm, the Perseus Arm, and the Outer Arm, respectively. Having added the most recent published results of astrometric measurements, we produced a sample containing data on 130 masers.

(5) We supplemented the well-known catalog of HII regions (Russeil 2003) with new photometric estimates of the distances to several star-forming regions collected in Russeil et al. (2007) and Moisés et al. (2011). From this catalog we took only those distances that were obtained photometrically. We assume the relative error of such distances to be 20%.

RESULTS AND DISCUSSION

Table 3 presents the results of our determinations of the Sun’s distance from the symmetry plane Z_{\odot} and the vertical disk scale height h_i , $i = 1, 2, 3$ that we obtained based on models (1)–(3) using the samples of various objects. These parameters and their errors were found by fitting the models to the histograms and through Carlo simulations. For this purpose, we constructed the histograms with a step of 10 pc in Z coordinate. Figure 1 shows the histogram of the Z distribution of OB associations with a step of 25 pc for better clarity.

Note that we actually have two sets of data of different ages. Masers, OB associations, HII regions, and Wolf–Rayet stars constitute the group of the youngest objects, while Cepheids form the second group of older objects. As can be seen from Table 3, the values of h_i found for the first group of objects agree satisfactorily between themselves, except for the masers. We will discuss the masers below. There is good agreement in the determinations of Z_{\odot} from the samples of all objects without exceptions. The histograms of the Z distribution of masers, HII regions, Wolf–Rayet stars, and a sample of 496 Cepheids are presented in Fig. 2.

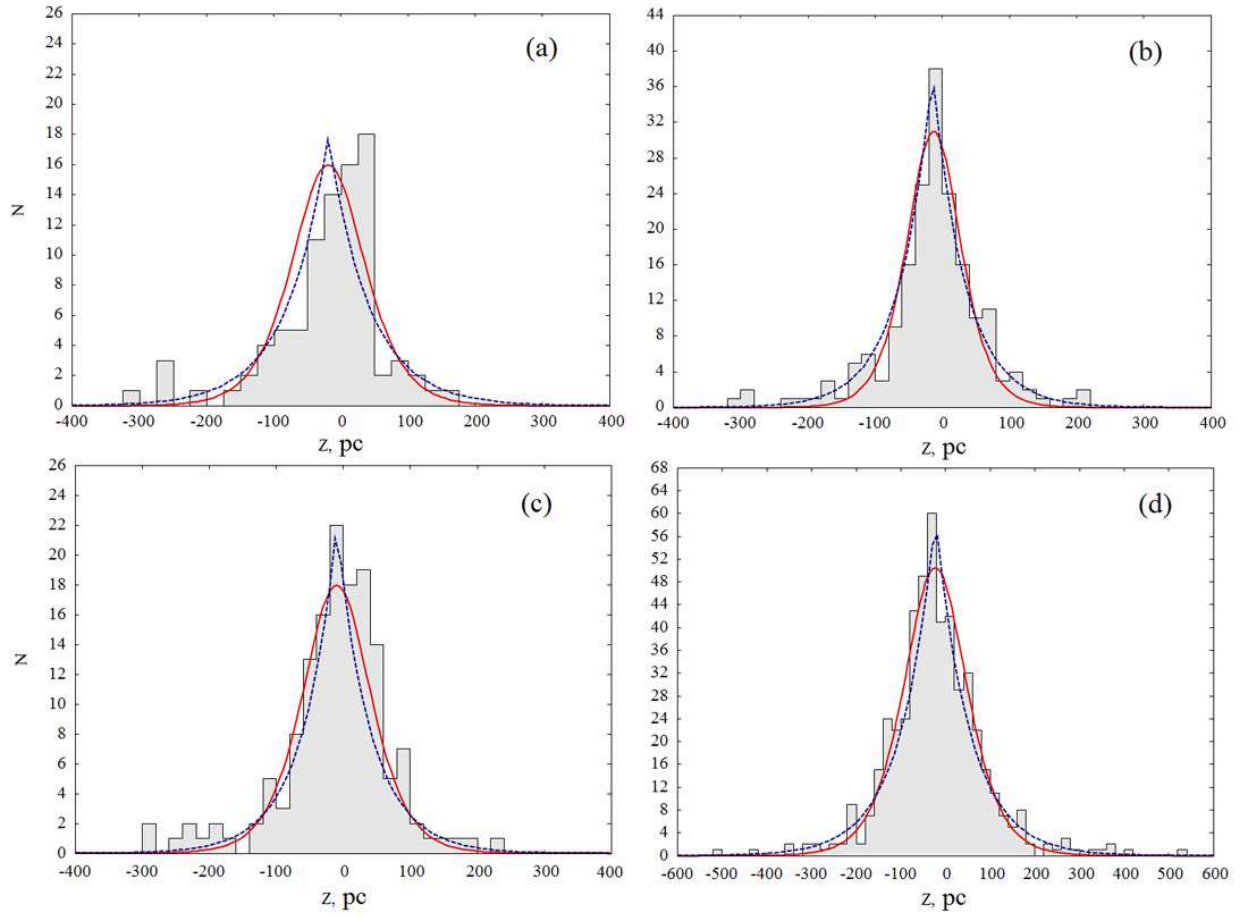


Рис. 2: Histogram of the Z distribution of masers a), HII regions b), Wolf-Rayet stars c), and Cepheids d); the dashed and solid lines curves on all panels represent models (1) and (2), respectively.

OB Associations

The three model fitting curves constructed with the parameters from Table 3 are plotted in Fig. 1. From the figure we can see no significant differences between all three curves, especially between curves (2) and (3). Different authors simply use different models based on the formulated problems and personal preferences. For example, the convenience of using model (1) lies in the fact that the distribution of objects in a logarithmic scale is fitted by two line segments (see, e.g., Fig. 3 in Piskunov et al. (2006)). Since curves (2) and (3) virtually coincide, we restricted ourselves to the two models (1) and (2) in Fig. 2.

HII Regions

The results of our analysis of HII regions are valuable in that we use only the distances derived photometrically from their central stars. It is interesting to compare our results to those obtained using indirect distance estimation methods.

Paladini et al. (2004) analyzed the Z distribution of 550 HII regions. Their distances were estimated partly by the kinematic method from the Galactic rotation curve and partly from the luminosity–diameter correlation. Therefore, their quality is not high. Nevertheless, these authors found the negative mean coordinate $Z_{\odot} = -11.3$ pc and the vertical disk scale height $h_3 = 52$ pc that agree satisfactorily with those we found.

Bronfman et al. (2000) studied 748 star-forming regions and H_2 clouds distributed over the entire Galaxy. They used the kinematic distances. These authors found $Z_{\odot} \approx -5$ pc and $h \approx 40$ pc (here, h is the half-width at half-height of the Gaussian distribution) from the HII regions and $Z_{\odot} \approx -6$ pc and $h \approx 60$ pc from the molecular hydrogen clouds. Since a very wide solar neighborhood was used here, significant differences in the Z_{\odot} determinations from northern ($0^\circ < l < 180^\circ$) and southern ($180^\circ < l < 360^\circ$) sky objects were found. In spite of this, the vertical scale heights are in satisfactory agreement with our estimates.

Wolf–Rayet Stars

Out of the total number of 354 Wolf-Rayet stars, there are 148 stars in the solar neighborhood with a radius $r < 4.5$ kpc. This sample is a factor of 1.5 larger than that analyzed by Conti and Vacca (1990). The value of $h_2 = 47.8 \pm 3.9$ pc we found is in excellent agreement with the result, $h_2 = 45 \pm 5$ pc, obtained by Conti and Vacca (1990).

Note that in comparison with all of the remaining samples, the values of h_i that we found from the Wolf-Rayet stars have the largest errors. This is because the individual distance errors for 246 stars from the list by Rosslove and Crowther (2015) occasionally reach $\approx 30\%$.

Cepheids

When analyzing the spatial distribution of Cepheids, Bobylev (2013) showed that the disk warp at distances $r > 4$ kpc affects significantly the calculation of Z_{\odot} . Therefore, we used this constraint on the Cepheid distances. In the range of heliocentric distances $r < 4$ kpc, the catalog of Mel’nik et al. (2015) contains 496 Cepheids with various pulsation periods

Таблица 3: Determinations of the Sun’s distance from the symmetry plane Z_{\odot} and the vertical disk scale height h_i , $i=1,2,3$ in the paper based on models: (1)–(3)

Z_{\odot} , pc	h_1 , pc	h_2 , pc	h_3 , pc	Sample
-19 ± 4	61 ± 4	51 ± 3	58 ± 3	90 masers, $r < 4$ kpc
-16 ± 2	44.9 ± 2.5	40.2 ± 2.1	46.9 ± 2.3	91 OB associations, $r < 3.5$ kpc
-15 ± 3	48.6 ± 2.5	48.4 ± 2.5	48.6 ± 2.5	187 HII regions, $r < 4.5$ kpc
-10 ± 4	51.3 ± 3.7	47.8 ± 3.9	54.8 ± 3.5	148 Wolf–Rayet stars, $r < 4.5$ kpc
-23 ± 2	70.2 ± 2.4	60.1 ± 1.9	69.6 ± 2.4	246 Cepheids, $\bar{t} \approx 75$ Myr, $r < 4$ kpc
-24 ± 2	83.8 ± 2.4	72.5 ± 2.3	83.2 ± 2.8	250 Cepheids, $\bar{t} \approx 138$ Myr, $r < 4$ kpc
-23 ± 2	76.4 ± 1.8	66.2 ± 1.6	76.6 ± 1.9	496 Cepheids, $\bar{t} \approx 107$ Myr, $r < 4$ kpc

P . We additionally divided the entire sample into two equal (in the number of stars) parts depending on the pulsation period with the boundary $P = 5.5$ days.

Several calibrations proposed to estimate the individual ages of Cepheids (t) from the pulsation period are known. We used the calibration from Efremov (2003),

$$\log t = 8.5 - 0.65 \log P, \quad (4)$$

derived by this author from Cepheids belonging to open clusters in the Large Magellanic Cloud. As a result, we have two samples of Cepheids with mean ages $t \approx 75$ and ≈ 138 Myr, while the mean age of the entire sample of 496 stars is ≈ 107 Myr. The theoretical calibration from Bono et al. (2005), $\log t = 8.31 - 0.67 \log P$, for Cepheids with a mean metallicity of 0.02 typical of Galactic stars is also known. The experience of its application shows (Bobylev and Bajkova 2012) that, in this case, the mean age of Cepheids turns out to be a factor of 1.5 younger than that based on calibration (4).

As can be seen from Table 3, owing to the large number of Cepheids, the values of Z_{\odot} and h found from them are highly accurate. It can be seen from Fig. 2 that the distribution of Cepheids is among the best ones from the standpoint of its symmetry. The distribution of HII regions is only slightly inferior to it, while the distributions of Wolf-Rayet stars and masers are most asymmetric.

We can also see that the vertical scale height h increases with increasing age of the sample stars. On the whole, this is in agreement with the results of the analysis of open star clusters with different ages performed, for example, by Bonatto et al. (2006) or Piskunov et al. (2006). It should be noted that the estimates of these authors disagree noticeably for the oldest open clusters. For example, Piskunov et al. (2006) found $h_1 = 61 \pm 6$ pc for the sample of open clusters with ages $\log t > 8.6$ (older than ≈ 400 Myr), which is half the value of $h_1 = 150 \pm 27$ pc obtained by Bonatto et al. (2006) from a sample of clusters with ages in the range 0.2–1 Gyr. The relation between the vertical disk scale height and the age of stars found by Buckner and Froebrich (2014) from the data on open star clusters is of interest in this connection. As can be seen from Fig. 6 of these authors, h is about 40 pc for clusters with ages of ≈ 1 Myr, 50 pc for clusters with ages of ≈ 10 Myr, reaches about 100 pc at an age of ≈ 1 Gyr, and only then does it begin to increase sharply to 550 pc at an age of ≈ 3.5 Gyr.

Masers

We used the data on maser sources that are associated mainly with massive protostars located in regions of active star formation. Therefore, one might expect that the values of h found from the sample of masers will not exceed those found from the HII regions, OB associations, and Wolf-Rayet stars. However, but this does not hold.

The sample of masers is peculiar in that their observations aimed at determining the trigonometric parallaxes are performed from the Earth's northern hemisphere. The parallax was determined using the Australian radio interferometer only for one source from the southern hemisphere. As a result, only the first and second quadrants are well filled in Galactic coordinates, while the fourth quadrant still remains almost empty (Fig. 2 in Bobylev and Bajkova (2014)).

We can conclude that to realize the existing high potential of these data, we should wait for the appearance of trigonometric parallax determinations with interferometers in the Earth's southern hemisphere. Such observations are currently being performed.

The Mean Value of Z_{\odot}

Based on the Z_{\odot} determinations from Table 3, we calculated the mean value of $Z_{\odot} = -16 \pm 2$ pc (the dispersion here is 4 pc, while 2 pc is the error of the mean). For this purpose, we used of four samples: (1) OB associations, (2) HII regions, (3) Wolf-Rayet stars, and (4) 496 Cepheids. This is a new estimate. It agrees satisfactorily with the results listed in Table 1, in particular, with the mean value of $Z_{\odot} = -18.6 \pm 1.4$ pc.

Estimating the Number of OB Associations in the Galaxy

Based on the derived parameters, we can calculate the surface, $\Sigma(Z)$, and volume, $D(Z)$, densities of objects. For this purpose, let us rewrite Eq. (1) in terms of the density $D(Z)$:

$$D(Z) = D(Z_{\odot}) \exp\left(-\frac{|Z - Z_{\odot}|}{h_1}\right). \quad (5)$$

The surface and volume densities are related by the relation (Piskunov et al. 2006)

$$\Sigma(Z) = 2D(Z_{\odot})h_1 \left[1 - \exp\left(-\frac{|Z - Z_{\odot}|}{h_1}\right)\right], \quad (6)$$

where $\Sigma(Z)$ denotes the surface density in a layer of thickness $2|Z - Z_{\odot}|$. We can estimate the total number of objects in the Galaxy N_{tot} using the relation (Piskunov et al. 2006)

$$N_{tot} = 2\pi \sum \int_0^{R^{lim}} \exp\left(-\frac{R - R_{\odot}}{L_d}\right) R dR, \quad (7)$$

where R is the distance from the star to the Galactic center, R^{lim} is the Galactocentric radius of the disk, L_d is the radial disk scale length, and $\Sigma = N_f/\pi d_{xy}^2$ is the surface density in the solar neighborhood found by assuming the sample to be complete, where d_{xy} is the sample completeness radius in the XY plane and N_f is the number of objects

in this sample. Just as in Piskunov et al (2006), we take $L_d = 3.5$ kpc and $R_\odot = 8$ kpc, which correspond to the model from Bahcall and Soneira (1980).

We use this approach to calculate the total number of OB associations, because we can easily compare the result with the estimates of the total number of open clusters in the Galaxy. Such estimates can be found, for example, in Piskunov et al. (2006) or Bonatto et al. (2006). Actually, the Scorpio–Centaurus OB association nearest to the Sun is known to contain about ten open clusters; the picture in the younger association in Orion is similar. Therefore, the expected number of young clusters in an association must be about ten.

According to the data in Table 3 for the sample of OB associations, we have $h_1 = 44.9$ pc and $Z_\odot = -16$ pc. We then estimated our sample of OB associations to be complete in the solar neighborhood with the radius $d_{xy} = 1.87$ pc. This neighborhood contains $N_f = 67$ associations. With these parameters, we find the surface and volume densities to be $\Sigma = 6$ kpc $^{-2}$ and $D(Z_\odot) = 50.6$ kpc $^{-3}$, respectively.

As a result, we found that $N_{tot} = 4949$ OB associations could be within the disk of radius $R_{lim} = 15$ kpc. Here, we see agreement with the result of Piskunov et al. (2006), where the total number of open clusters in the Galaxy was found under the same conditions to be $N_{tot} = 93000$. Indeed, these estimates show that, on average, one OB association contains $93000/4949 \approx 19$ clusters.

Bonatto et al. (2006) estimated the total number of clusters in the Galaxy to be $1.8\text{--}3.7 \times 10^5$. In this case, one OB association must contain from 36 to 74 clusters. Here, the agreement with our results is considerably poorer.

Since OB associations can contain only young clusters, we can conclude that our estimates agree with the results of other authors in order of magnitude.

Note that our estimate of $N_{tot} = 4949$ may be considered (with some reservations) as an upper limit on the number of OB associations. The Sun is located near two spiral arms, where the orbits of gas clouds come close together, and the frequency of collisions between clouds increases; such stimulated star formation leads to the birth of OB associations. Furthermore, the Sun may be located near the bar-induced Lindblad outer resonance. Therefore, there may be more gas here than at other radii.

CONCLUSIONS

We obtained new estimates of the Sun’s distance from the symmetry plane Z_\odot and the vertical disk scale height h using samples of various objects. For this purpose, we took the currently available data on (1) 91 stellar OB associations, (2) 187 HII regions, (3) 148 Wolf-Rayet stars, (4) 90 maser sources in regions of active star formation, and (5) 496 classical Cepheids.

To each of these samples, we applied three models of the density distribution: the model of an exponential distribution, the model of a self-gravitating isothermal disk, and the model of a Gaussian density distribution. We showed that the derived vertical disk scale heights h depend on the age of sample objects when using any of these three models.

It turned out that the values of h found from the sample of masers deviate noticeably from this dependence. We concluded that the values of h found from the sample of masers are not reliable. This is because the sample available to date is so far dominated by

northern-sky masers (Galactic longitudes $0^\circ < l < 180^\circ$). The remaining four samples have a uniform longitude distribution; obtained quite reliable estimates from them.

Based on the individual determinations of Z_\odot from four different samples (without the sample of masers), we calculated the mean value of $Z_\odot = -16 \pm 2$ pc. This is a new estimate, but, at the same time, it is in good agreement with other known estimates of this quantity.

We showed the vertical disk scale height to be determined with the smallest errors based on the model of a self-gravitating isothermal disk (model (2)), using which we found $h = 40.2 \pm 2.1$ pc from OB associations, $h = 47.8 \pm 3.9$ pc from Wolf-Rayet stars, $h = 48.4 \pm 2.5$ pc from HII regions, and $h = 66.2 \pm 1.6$ pc from Cepheids.

We estimated the surface and volume densities from the sample of OB associations to be $\Sigma = 6 \text{ kpc}^{-2}$ and $D(Z_\odot) = 50.6 \text{ kpc}^{-3}$, respectively. Based on these estimates, we showed that there could be about 5000 OB associations in the Galaxy.

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